

## What Physics Can We Drop Without Breaking Engineering: A Cold Audit

Douglas C. Youvan

[doug@youvan.com](mailto:doug@youvan.com)

[www.youvan.ai](http://www.youvan.ai)

October 6, 2025

Engineering runs on balance laws, constitutive models, and calibration loops—not on grand unifiers. This paper offers an unflinching, utility-first audit of physics topics whose removal would not measurably degrade day-to-day engineering outcomes across civil, mechanical, electrical, chemical, and most aerospace practice. We formalize criteria for dispensability (operational impact, error budgets, model dependence, and verification pathways), then classify domains from “safest to drop” to “do not touch.” High-energy model details, cosmology beyond weak-field needs, quantum interpretations, strong-field GR, renormalization-group formalism, path integrals, gauge-geometric language for classical EM/fluids, and exotic topological phases are shown to be largely orthogonal to production workflows. Areas “removable with care”—quantum information formalism, advanced non-equilibrium statistical mechanics, and turbulence theory—matter only in specific niches or R&D frontiers. We contrast these with non-negotiables: Newtonian mechanics, continuum balances, thermodynamics, practical electromagnetism, semiconductor basics, probability/statistics, numerical linear algebra/optimization, and controls. Case studies map removal impacts to concrete artifacts: bridges, pumps, drives, process units, avionics, and power systems. The goal is not provocation but clarity: isolate what actually carries the load in design, verification, and operations, and surface where theoretical elegance is a luxury rather than a dependency. No romance—only what ships.

Keywords: engineering pragmatics, conservation laws, dispensability audit, nonessential physics, curricula design, verification and validation, modeling error budgets, production workflows.

A collaboration with GPT-5. CC4.0. 35 pages.

## Outline

### 1. Problem Statement and Scope

- 1.1 Definitions: “affect engineering,” “production workflow,” “impact threshold”
- 1.2 Disciplines covered and excluded edge industries

### 2. Method: How We Decide Dispensability

- 2.1 Criteria: operational impact, error budgets, calibration closure
- 2.2 Evidence classes: ablation reasoning, case substitution, sensitivity to assumptions
- 2.3 Levels: safe to drop / removable with care / do not touch

### 3. What Engineering Actually Uses

- 3.1 Balance laws (mass, momentum, energy, charge)
- 3.2 Constitutive models and their validation envelopes
- 3.3 Numerics, controls, and metrology as the closing loop

### 4. Safest to Drop

- 4.1 Particle model specifics (CKM/PMNS, Higgs details, SUSY, GUTs)
- 4.2 Cosmology beyond weak-field GR (inflation, dark-energy EoS)
- 4.3 Quantum interpretations (Copenhagen vs Bohm vs Many-Worlds)
- 4.4 Strong-field GR topics (BH thermodynamics, Penrose processes)
- 4.5 Renormalization-group formalism (as formalism)
- 4.6 Path-integral mechanics (as a formulation)
- 4.7 Gauge/differential-forms language for EM/fluids (keep vector calculus form)
- 4.8 Exotic topological phases (QHE/anyons) outside niche devices

### 5. Removable With Care (Niche-Critical)

- 5.1 Quantum information formalism (qubits/channels/entropies)
- 5.2 Advanced non-equilibrium stat mech (Kubo, fluctuation theorems)
- 5.3 Advanced turbulence theory (cascades/intermittency) vs RANS/LES practice

## **6. Do Not Touch**

- 6.1 Newton + work-energy + momentum
- 6.2 Continuum mechanics (Navier–Stokes, elasticity/plasticity)
- 6.3 Thermodynamics (1st/2nd law, exergy, cycles)
- 6.4 Practical electromagnetism (circuits, waves, transmission lines)
- 6.5 Semiconductor/laser basics for EE
- 6.6 Probability/statistics; numerical linear algebra/optimization
- 6.7 Control theory (classical and state-space)

## **7. Case Studies by Sector**

- 7.1 Civil/structural: load paths, safety factors, codes, FEA
- 7.2 Mechanical: turbomachinery, heat exchangers, drivetrain control
- 7.3 Electrical: power systems, drives, EMC, RF links
- 7.4 Chemical/process: mass-energy balances, kinetics in practice
- 7.5 Aerospace (conventional): flight dynamics, GN&C, weak-field relativity only

## **8. Failure Modes of Wrong Removals**

- 8.1 Where ablations backfire: semiconductors without band theory
- 8.2 Hidden dependencies through materials data and EM compatibility
- 8.3 When “model works” because metrology patched it—until it doesn’t

## **9. Implications**

- 9.1 Curricula and licensing exams: rebalancing theory vs utility
- 9.2 Toolchains: enforce conservation, track validation envelopes
- 9.3 R&D vs production: where the frontier still needs full theory

## **10. Limits of This Audit**

- 10.1 Edge industries (quantum tech, fusion, topological devices)
- 10.2 Regime changes and future coupling risks
- 10.3 What “no effect” means in quantified tolerances

## **11. Conclusion: What Carries the Load**

- 11.1 The irreducible spine of engineering practice
- 11.2 What can go—and why that clarity matters

## **References**

## 1) Problem Statement and Scope

### 1.1 Definitions: “affect engineering,” “production workflow,” “impact threshold”

#### **Affect engineering.**

In this audit, a topic “affects engineering” iff removing it (or its practical surrogates) produces a measurable degradation in one or more standard delivery objectives within validated operating envelopes. Concretely, degradation means any of:

- **Safety margin erosion:**  $\geq 10\%$  reduction in prescribed factor of safety or breach of code-mandated checks.
- **Performance miss:**  $\geq 1\%$  deviation in a contract KPI that is outside metrology noise and model tolerances (e.g., specific fuel consumption, efficiency, gain/phase margins, BER, pressure drop).
- **Cost/schedule impact:**  $\geq 2\%$  increase in lifecycle cost (LCC) or  $\geq 5\%$  slip on the critical path attributable to analysis/design rework or test inflation needed to compensate for theory loss.
- **Regulatory non-compliance:** inability to produce evidence artifacts required by standards (traceable balances, EMC, reliability, SIL/ASIL).
- **Operability/reliability hit:** MTBF/availability drops beyond agreed thresholds; alarms/controls lose stability or robustness margins.

#### **Production workflow.**

The end-to-end sequence used to ship and sustain engineered systems:

1. **Requirements & constraints:** codes, KPIs, loads, environments.
2. **Architecture & preliminary sizing:** back-of-envelope physics, rule-of-thumb scaling, past data.
3. **Detailed modeling:** balance laws + constitutive models; linear algebra; optimization; controls.
4. **Verification & validation (V&V):** unit tests, bench/rig, CFD/FEA correlation, HIL/SIL, measurement closure.
5. **Certification & release:** standards evidence, safety cases, documentation.
6. **Manufacturing & QA:** tolerances, SPC, acceptance tests.
7. **Operations & monitoring:** calibration, trending, fault management, updates.

A physics topic is **indispensable** if its removal breaks one or more of these stages in a way that cannot be substituted by empiricism (data/correlation), numerics (discretely conservative schemes), or standards practices (derating, factors, tests) without exceeding impact thresholds.

### **Impact threshold.**

A crisp, audit-ready bar: if ablation of a topic can be masked by (a) swapping in simpler theory, (b) adding tests/guardbands with < 2% LCC and < 5% schedule penalty, and (c) keeping safety/performance within contract tolerances, then the topic is *dispensable for production*. If not, it is *non-removable*.

---

## **1.2 Disciplines covered and excluded edge industries**

### **Covered (mainstream, high-volume or code-driven practice):**

- **Civil/Structural:** buildings, bridges, geotech, water, HVAC; code-centric designs using statics, elasticity, materials allowables, and load combinations.
- **Mechanical:** turbomachinery, heat exchangers, drivetrains, mechanisms; thermodynamics, fluid/heat transport, fatigue, rotordynamics.
- **Electrical & Power:** power systems and protection, drives, EMC/EMI, RF links under classical EM; KCL/KVL, transmission lines, shielding/grounding practice.
- **Controls & Mechatronics:** classical/state-space control, observers, system ID, robustness; actuation and sensing under linear/nonlinear models.
- **Chemical/Process:** mass/energy balances, reaction engineering at reactor scale, separations, process control, safety (HAZOP/LOPA).
- **Conventional Aerospace:** flight dynamics, structures, propulsion under weak-field relativity corrections (e.g., GPS time dilation) but not strong-field GR.

### **Excluded (edge/nascent or fundamental-physics-sensitive):**

- **Semiconductor device R&D at the physics frontier:** hot-carrier effects, sub-7 nm variability, advanced EUV resists, spintronics; depends on solid-state quantum theory and materials physics beyond simple band models.
- **Quantum technologies:** quantum communication, sensing, and computing; requires quantum information formalism, open-system dynamics, decoherence control.
- **Topological and strongly correlated materials:** anyons, fractional QHE, unconventional superconductivity; relies on field-theoretic/topological methods.

- **Fusion & HEDP:** high-beta MHD stability, kinetic effects, radiation hydrodynamics; sensitive to advanced plasma physics and transport theory.
- **Relativistic/astrodynamics beyond weak field:** strong-field GR, black-hole thermodynamics; not representative of mainstream engineering.
- **Biotech at molecular-mechanism scale:** protein design, quantum biology claims; outside conventional process-scale ChemE.

#### Rationale for scope.

The covered set maps to sectors where **balance laws + validated constitutive models + numerics + standards** dominate outcomes, and where metrology can close the loop without invoking deep, frontier theory. The excluded set contains domains whose **performance envelope or feasibility** is materially tied to advanced physics; ablation there would cross the impact thresholds defined above.

## 2) Method: How We Decide Dispensability

### 2.1 Criteria: operational impact, error budgets, calibration closure

**Operational impact.** We score whether removing a physics topic causes any of:

- Safety margin erosion (code factors, stability margins) beyond contract limits.
- KPI drift beyond accepted tolerances (efficiency, BER, tracking error, pressure drop, EMI).
- Cost/schedule penalties to compensate (extra tests, overdesign) beyond agreed caps.

**Error budgets.** Each deliverable owns a top-down error budget. We check whether ablation:

- **Adds irreducible bias** (cannot be averaged out) to the budget.
- **Inflates variance** such that the rolled-up root-sum-square exceeds the KPI limit.
- **Forces surrogate parameters** (fudge factors) that are unstable across environments, invalidating reuse.

**Calibration closure.** A topic is dispensable only if its loss can be closed by:

- **Metrology:** sensors, acceptance tests, site calibration that bound residuals within budget.
- **Numerics:** conservative discretizations ensuring mass/energy/momentum accounting without the ablated theory.

- **Standards and guardbands:** derating, worst-case envelopes that provably keep risk  $\leq$  target levels.  
If closure requires open-ended tuning, non-portable fits, or recurring re-qualification, the topic is not dispensable.
- 

## 2.2 Evidence classes: ablation reasoning, case substitution, sensitivity to assumptions

### Ablation reasoning (delete and observe).

- Construct a minimal **surrogate workflow** with the topic removed.
- Hold requirements, loads, and acceptance tests constant.
- Compare: (i) margins, (ii) KPI deltas, (iii) V&V effort, (iv) recurring O&M impact.
- Pass if all deltas lie within thresholds and no new single-point failures appear.

### Case substitution (swap equivalent practice).

- Replace the theory with an **empirical or simpler theoretical** stand-in (e.g., band theory  $\rightarrow$  tabulated device curves; RG  $\rightarrow$  scale fits).
- Demonstrate **transferability** across at least two distinct regimes (e.g., temperature bands, Reynolds ranges, EMI environments).
- Fail if substitution works only via local curve-fit that collapses at neighboring conditions.

### Sensitivity to assumptions (stress the premises).

- Perturb modeling assumptions the removed topic formerly constrained (e.g., linearity, stationarity, isotropy).
  - Run **local and global sensitivity** (one-at-a-time and Sobol-style) to check whether KPI variance explodes.
  - If the topic's absence makes results hypersensitive to poorly measured inputs, it is not dispensable.
- 

## 2.3 Levels: safe to drop / removable with care / do not touch

### Level A — Safe to drop.

- **Definition:** Removal yields  $\leq 1\%$  KPI change,  $\leq 2\%$  lifecycle cost increase,  $\leq 5\%$  schedule slip, zero standards violations, and calibration closes with fixed, portable procedures.

- **Evidence required:** One successful ablation on a representative project **plus** a second-context replication.
- **Examples (indicative):** HEP model details, cosmology beyond weak-field, quantum interpretations, path-integral formalism (as a formulation).

#### **Level B — Removable with care.**

- **Definition:** Removal is acceptable **only** with explicit guardbands or extra tests; effect sizes small but non-negligible; valid in mainstream regimes, risky at edges.
- **Controls:** Documented applicability envelope; mandatory design review gate to confirm stays inside bounds; budget line for compensating tests.
- **Examples (indicative):** Advanced turbulence theory (when RANS/LES + validation suffice), non-equilibrium stat-mech formalisms in macro-scale plants, quantum-info formalism outside quantum products.

#### **Level C — Do not touch.**

- **Definition:** Removal breaks balance laws, destabilizes control, voids compliance, or inflates error budgets past spec—even with aggressive testing.
- **Hard bars:** Mass/energy/momentum/charge balances; practical EM for circuits/fields; thermodynamics; semiconductor basics in EE; numerical linear algebra/optimization; control theory.
- **Outcome:** Topic is a structural dependency; ablation invalidates the production workflow.

**Governance note.** Classification is **artifact- and regime-specific**. A topic may be Level A for civil HVAC and Level C for EUV lithography. Each designation must cite its ablation record, substitution proof, sensitivity results, and calibration plan.

### **3) What Engineering Actually Uses**

#### **3.1 Balance laws (mass, momentum, energy, charge)**

##### **Core form (control volume):**

For any extensive quantity  $U$  with density  $u$  and flux  $F$ , engineers use balance laws in the form  $d/dt \int_{CV} u \, dV + \oint_{CS} F \cdot n \, dA = \sum \text{sources/sinks}$ .

Specializations:

- **Mass:** continuity; for incompressible flow,  $\text{div}(\mathbf{v}) = 0$  as a constraint.
- **Momentum:** Navier–Stokes/Euler in integral or differential form; jump conditions across shocks; reaction forces from flux differences.
- **Energy:** first law with work/heat terms; for reacting/phase-change systems, enthalpy balances; exergy for quality-of-energy accounting.
- **Charge/EM:** KCL/KVL (lumped), Poynting theorem and transmission-line equations (distributed); Maxwell used in vector-calculus form for RF/EMC.

### What practitioners actually do

- Choose CVs aligned with hardware boundaries (ducts, tanks, PCB nets).
- Enforce *discrete* conservation in meshes and circuit nets (finite volume, nodal analysis).
- Track invariants through interfaces: mass flow continuity, momentum jumps, energy in/out, net current = 0 at nodes.

**Why this survives ablations:** These balances are empirically validated and enforced by numerics and test, independent of high-level theory.

---

## 3.2 Constitutive models and their validation envelopes

**Constitutive closure = “how stuff behaves.”**

Balances need material laws to close:

- **Fluids:** Newtonian  $\tau = \mu * \text{grad}_{\text{sym}}(\mathbf{v})$ ; non-Newtonian fits (power-law, Bingham); turbulence via RANS models (k-epsilon, k-omega), LES subgrid closures.
- **Solids:** linear elasticity (Hooke); plasticity (von Mises, kinematic hardening); creep/fatigue S-N or epsilon-N fits; fracture ( $K_{Ic}$ , J-integral).
- **Heat/mass transfer:** Fourier, Newton cooling  $h$ , radiation  $\sigma * T^4$ , Fick diffusion; boiling/condensation correlations.
- **EM materials:**  $\epsilon_r$ ,  $\mu_r$ ,  $\sigma$ ; skin depth, dielectric loss tangents; vendor S-parameters for components.
- **Chem/kinetics:** Arrhenius rates, equilibrium  $K$ , activity/transport correlations; multiphase slip/holdup maps.

### Validation envelope (where the model is trusted)

- **Range:** T, p, composition, Re/Ma/Kn, strain rate, frequency.
- **Quality:** residuals vs data, cross-validated fits, uncertainty bands.
- **Portability:** performance across facilities/vendors; environmental robustness.

### Workflow

1. Pick the simplest law that passes required accuracy in the envelope.
2. Fit to reliable data; document parameter uncertainty.
3. Confirm with spot tests at the edges; freeze the envelope in the spec.
4. Add guardbands where model form is known to drift (e.g., transition, high Ma, near yield).

**Why this keeps engineering standing:** Even if deep theory changes, envelope-validated constitutive laws plus tests still deliver parts that meet spec.

---

## 3.3 Numerics, controls, and metrology as the closing loop

### Numerics (make the balances discrete and solvable)

- **Conservative schemes:** finite volume for CFD/heat; ensure local mass/energy/momentum balance cell-by-cell; shock-capturing where needed.
- **Stable time marching:** CFL-limited explicit or A-stable implicit; stiffness handling in reacting/thermal systems.
- **Linear algebra & optimization:** sparse solves ( $Kx=f$ ), eigenvalue checks for stability, least-squares/regularization for ID; NLP/QP for design.
- **Verification:** code-to-code and method-of-manufactured-solutions (MMS); mesh/time-step refinement until KPI deltas are within budget.

### Controls (stabilize and reject disturbances)

- **Classical/state-space:** PID with anti-windup; LQR/LQG; H-infinity/ $\mu$  for robustness; feedforward + observers (Kalman, Luenberger).
- **Margins:** gain/phase, Nyquist, structured singular value; slew/actuator limits; integrator windup guards.

- **Implementation:** sampling, quantization, latency; discrete-time pole placement; bumpless transfer; fault-tolerant modes.

### **Metrology (prove it works, bound the unknowns)**

- **Calibration hierarchy:** primary standards -> secondary -> field instruments; traceability and uncertainty budgets (ISO GUM style).
- **Acceptance tests:** FAT/SAT, HIL/SIL, golden units, SPC on critical parameters; MSA (gage R&R).
- **Monitoring:** trend KPIs, residuals vs digital twins, control-chart alarms, on-line parameter ID to catch drift.

### **Closing the loop (V&V triangle)**

1. **Conservation in the solver** ensures physics accounting even with simplified theory.
2. **Control robustness** absorbs model mismatch and disturbances inside design margins.
3. **Metrology** measures, calibrates, and certifies that residual deviations are within the error budget.

### **Bottom line for Section 3:**

Engineering success is the product of (i) hard conservation, (ii) constitutive models *validated inside declared envelopes*, and (iii) numerics+controls+metrology that detect and bound deviation. This triad is what carries production workloads—largely orthogonal to whether elegant, high-level physics explanations are retained or ablated.

## **4) Safest to Drop**

### **4.1 Particle model specifics (CKM/PMNS, Higgs details, SUSY, GUTs)**

**What it is.** Quark/lepton mixing matrices (CKM/PMNS), electroweak symmetry breaking details, speculative extensions (SUSY, GUTs).

**Engineering dependency.** None for civil/mech/EE/chem process or conventional aerospace; material data and device curves are empirical.

**What you lose.** Explanations for mass/mixing hierarchies; HEP design rationales.

**Guardrails.** Keep macroscopic conservation and radiation/matter-interaction data (stopping powers, cross-sections) from handbooks.

**Not safe when...** Designing particle detectors, radiation therapy beamlines, or shielding for high-fluence facilities (keep the cross-section models; even there CKM/PMNS values themselves are not design inputs).

## 4.2 Cosmology beyond weak-field GR (inflation, dark-energy EoS)

**What it is.** Early-universe models, dark-energy parameterizations, large-scale structure theory.

**Engineering dependency.** None at product scales; GPS/geodesy need only weak-field GR corrections.

**What you lose.** Coherent origin-story for the universe; no bearing on pumps, bridges, or drives.

**Guardrails.** Retain weak-field GR time dilation and geoid models for navigation and timing.

**Not safe when...** You work in cosmology or astrophysical instrumentation targeting those parameters.

## 4.3 Quantum interpretations (Copenhagen vs Bohm vs Many-Worlds)

**What it is.** Competing ontologies for the same operational quantum predictions.

**Engineering dependency.** Semiconductor, laser, and sensor design rely on band structure, rate equations, and measured device curves, not on interpretational stance.

**What you lose.** Philosophical clarity and some pedagogical pathways.

**Guardrails.** Keep operational quantum tools: Schrödinger/Heisenberg equations, band theory, Fermi levels, device compact models.

**Not safe when...** Doing foundations or thought-experiment work; still safe for production electronics.

## 4.4 Strong-field GR topics (BH thermodynamics, Penrose processes)

**What it is.** Physics near horizons, high curvature, and relativistic energy extraction.

**Engineering dependency.** None in terrestrial or near-earth systems; even deep-space navigation uses weak-field approximations.

**What you lose.** Insight into black-hole entropy and high-curvature phenomena; zero impact on certification, EMC, or structural checks.

**Guardrails.** Retain special relativity and weak-field GR corrections for timing and precise navigation.

**Not safe when...** Designing instruments intended for strong-field astrophysics.

## 4.5 Renormalization-group formalism (as formalism)

**What it is.** The RG machinery that explains scale dependence and universality in field theory/stat mech.

**Engineering dependency.** Day-to-day design uses empirical scaling, similarity, and nondimensional analysis; CFD/FEA are calibrated without explicit RG.

**What you lose.** First-principles rationale for why certain scale laws work; powerful unifying intuition for multiscale behavior.

**Guardrails.** Keep dimensionless analysis (Re, Ma, Pe, Fr), validated correlations, and uncertainty quantification across scales.

**Not safe when...** Researching critical phenomena, turbulence theory research, or multiscale materials at the physics frontier.

#### **4.6 Path-integral mechanics (as a formulation)**

**What it is.** Feynman's integral-over-histories, mathematically equivalent (where defined) to Hamiltonian/Lagrangian mechanics.

**Engineering dependency.** Controls, robotics, structural dynamics, and GN&C proceed with Newton/Hamilton/state-space; no need for path integrals.

**What you lose.** Elegant links to quantum/statistical formulations and some variational discretizations.

**Guardrails.** Keep Hamilton's principle, Lagrange multipliers, and state-space methods for optimization and control.

**Not safe when...** Doing quantum field theory or semiclassical asymptotics where the path-integral lens is the working tool.

#### **4.7 Gauge/differential-forms language for EM/fluids (keep vector calculus form)**

**What it is.** Potentials, gauge symmetry, and exterior calculus (differential forms) formulations of Maxwell and fluid equations.

**Engineering dependency.** Vector-calculus Maxwell (curl/div) and standard CFD/FEA suffice for circuits, RF, EMC, and fluid systems.

**What you lose.** Geometric clarity, coordinate-free proofs, and certain structure-preserving discretizations.

**Guardrails.** Retain transmission-line theory, Poynting theorem, boundary conditions, and vendor S-parameters; in fluids, keep conservative finite-volume schemes.

**Not safe when...** Developing structure-preserving solvers or working at the research interface of geometry and PDEs.

#### **4.8 Exotic topological phases (QHE/anyons) outside niche devices**

**What it is.** Quantum Hall effects, anyonic statistics, topological insulators/superconductors.

**Engineering dependency.** Mainstream products (civil/mech/EE power, RF, process) do not require these phases.

**What you lose.** Access to specialized sensors, metrology standards, and emerging quantum devices.

**Guardrails.** Keep classical solid-state (bands, mobility, scattering), materials handbooks, and reliability data.

**Not safe when...** Your product is a topological device or relies on quantized resistance standards in primary metrology (those groups must keep the physics, though downstream users can treat the standard as a black box).

**Section takeaway.** These topics are high-value for science and some niches, but ablation does not move the needles that production engineering is paid to hit: balances, envelopes, certification, cost, and schedule.

## 5) Removable With Care (Niche-Critical)

### 5.1 Quantum information formalism (qubits/channels/entropies)

**What it is.** The operational toolkit of quantum info: qubits and density matrices; CPTP maps (quantum channels); entropy and mutual information; error-correcting codes; resource theories.

**When it is safe to drop.** For mainstream EE/mechatronics/power/RF that treats quantum devices as black boxes with vendor curves (gain, noise figure, NEP, linewidth), you can proceed without qubit/channel formalism.

**Where it is not safe.** Products whose value proposition depends on quantum coherence or nonclassical correlations: QRNGs, QKD links, atomic clocks with entanglement-assisted readout, NV-diamond sensors, quantum memories, superconducting/ion-trap stacks.

#### Guardrails if removed.

- Treat devices via **measured transfer functions** and specs (S-parameters, noise spectral density, Allan deviation).
- Add **acceptance tests** that bound drift/decoherence indirectly (stability over T, B, vibration).
- Maintain **calibration intervals** short enough to catch coherence-loss surrogates.

#### Failure modes when dropped.

- Overstating security/performance because classical metrics hide **state-prep/measurement (SPAM) errors**.
- Environment-induced decoherence acting as hidden state channel; surprises during field deployment.

**Minimal metrics to keep.** T1/T2 or coherence time proxy, effective photon number, phase noise, contrast/visibility, detection efficiency; spec these empirically even if you omit the formalism.

## 5.2 Advanced non-equilibrium stat mech (Kubo, fluctuation theorems)

**What it is.** Linear response theory (Green–Kubo relations), fluctuation–dissipation, Jarzynski/Crooks-style nonequilibrium results, kinetic theory beyond simple closures.

**When it is safe to drop.** Macro-scale process plants and mechanical systems where **correlations and transport** are reliably captured by validated empirical laws (e.g.,  $Nu=f(Re,Pr)$ , Sherwood, Chilton–Colburn analogies, vendor heat/mass-transfer data).

**Where it is not safe.** Micro/nanoscale heat transfer, phonon/electron nonequilibrium, strongly driven soft-matter and reactive flows where **memory effects** and **nonlocal transport** dominate; high-rate additive manufacturing, ultrafast laser processing, cryogenic/vacuum systems with rarefaction (finite Knudsen number).

**Guardrails if removed.**

- Declare a **validation envelope** in  $Re$ ,  $Kn$ ,  $Pe$ ,  $Ma$ , dimensionless heating rate; forbid operations outside.
- Use **surrogate fits** tied to tightly matched experiments (geometry, surface finish, flow regime).
- Carry **uncertainty bands** on transport coefficients; propagate to KPI-level error budgets.

**Failure modes when dropped.**

- Hidden **rate dependence** (history effects) invalidates steady correlations.
- **Knudsen/ballistic transport** breaks Fourier/Fick closures, leading to thermal runaway or yield loss.

**Minimal metrics to keep.** Effective conductivity/diffusivity vs  $T$  and scale; relaxation times; Biot number bounds; hysteresis tests under rate sweeps to detect memory effects.

---

## 5.3 Advanced turbulence theory (cascades/intermittency) vs RANS/LES practice

**What it is.** First-principles understanding of energy cascades, intermittency corrections, multifractal models, and spectral laws beyond engineering closures.

**When it is safe to drop.** Industrial CFD where **RANS** ( $k$ –epsilon,  $k$ –omega, SST) or **LES/DES** models have been validated against canonical tests and relevant rigs; ducting, heat exchangers, external aerodynamics at moderate  $Ma$ , process lines, HVAC.

**Where it is not safe.** Edge cases: massive separation with control, hypersonics with strong shocks and real gas, rotating/stably stratified turbulence, high Re internal flows with strong buoyancy or swirl where **model-form error** dominates; certification-critical aero loads with small margin.

**Guardrails if removed.**

- Treat closures as **model hypotheses**; perform **model-form uncertainty quantification** (multi-model RANS, Bayesian calibration, EFD correlation).
- Enforce **grid and time-step convergence**; y+ and wall treatment audits; shock and separation resolution criteria.
- Use **wind-tunnel or rig data** to pin correction factors; document applicability ranges.

**Failure modes when dropped.**

- Non-portable tuning that collapses with small geometry or Reynolds changes.
- Underpredicted separation or overpredicted heat transfer leading to margin shortfalls.

**Minimal metrics to keep.** Residual convergence behavior; y+ distribution; integrated forces/heat flux vs test; sensitivity of KPIs to turbulence-model switches; correction factors with confidence intervals and traceability.

---

**Section takeaway.** These domains can be omitted **only** when you (i) prove that simpler surrogates plus testing keep KPIs within budget, (ii) declare and respect envelopes, and (iii) install monitoring to catch regime drift. Outside those conditions, the “removal” becomes an uncontrolled risk transfer.

## **6) Do Not Touch**

### **6.1 Newton + work-energy + momentum**

**What it is.** Newton’s laws; linear/angular momentum balances; work–energy theorem; impulse; virtual work.

**Why indispensable.** Every sizing and verification loop—loads, reactions, stability, impact, vibration—rests on these identities. They are the backbone of FEA pre/post-processing and test correlation.

**If removed.** Load paths cannot be computed or justified; safety factors lose meaning; dynamic certification (shock, drop, crash) fails audit.

**Keep at minimum.** Free-body diagrams, equilibrium, momentum/energy balances, D'Alembert form, impulse–momentum for transients.

## **6.2 Continuum mechanics (Navier–Stokes, elasticity/plasticity)**

**What it is.** Field equations for fluids/solids; conservation + constitutive closure; boundary/interface conditions.

**Why indispensable.** Pressure drops, heat transfer, aero/structural loads, stress/strain, fatigue—every major KPI depends on continuum predictions or their validated surrogates.

**If removed.** CFD/FEA lose governing equations; piping/ducting, aero loads, and structural integrity cannot be justified; code compliance collapses.

**Keep at minimum.** Reynolds transport theorem; Navier–Stokes/Euler; Hooke's law; yield/flow rules; fracture mechanics ( $K_{Ic}$ ,  $J$ ); contact models; jump conditions.

## **6.3 Thermodynamics (1st/2nd law, exergy, cycles)**

**What it is.** Energy and entropy balances; availability (exergy); cycles (Rankine/Brayton/Vapor compression); mixtures and phase change.

**Why indispensable.** Efficiency, fuel burn, COP, heat rates, compressor/expander maps, safety relief sizing—all require 1st/2nd law accounting. Exergy drives loss localization and upgrade decisions.

**If removed.** Energy/accounting becomes ad hoc; efficiency claims are non-auditable; hazards (overpressure, runaway) increase.

**Keep at minimum.** Control-volume energy/entropy balances; property methods (steam tables/EoS); cycle analysis; pinch/exergy analysis; safety relief calculations.

## **6.4 Practical electromagnetism (circuits, waves, transmission lines)**

**What it is.** KCL/KVL; lumped/distributed models; Maxwell in vector-calculus form; transmission lines, waveguides, antennas; EMC/EMI practices.

**Why indispensable.** Power systems stability, signal integrity, RF links, shielding/grounding, SAR/EMC compliance—production electronics and power grids rely on this.

**If removed.** PCB, harness, enclosure design turn trial-and-error; overvoltage/overcurrent protection and EMC certification fail; RF performance becomes non-reproducible.

**Keep at minimum.** Circuit laws; Poynting theorem; TL equations (reflection, VSWR, S-parameters); skin depth/loss; shielding/grounding rules; near-/far-field criteria.

## **6.5 Semiconductor/laser basics for EE**

**What it is.** Bands, carriers, junctions/MOSFET operation, noise; optoelectronic gain/threshold, linewidth; compact models.

**Why indispensable.** Device selection and derating, thermal design, noise/linearity budgets, link

budgets, timing—cannot be black-boxed reliably across environments without basic physics.

**If removed.** Wrong bias/thermal margins; reliability drops (BTI/HCI/EM); laser/LED links drift; timing closure and noise floors degrade unpredictably.

**Keep at minimum.** Band diagrams, diode/transistor equations, carrier mobility vs T, device SOA/derating, compact models (SPICE), laser threshold/efficiency, noise models.

## 6.6 Probability/statistics; numerical linear algebra/optimization

**What it is.** Uncertainty quantification, estimation, hypothesis tests, SPC; solvers (sparse/dense), eigen-analysis, conditioning; convex/nonconvex optimization.

**Why indispensable.** Requirements are probabilistic; sensors and ID need estimators; controllers and structures depend on eigenvalues; every solver/CFD/FEA hinges on linear algebra; design trades require optimization.

**If removed.** No credible tolerance stacks, reliability claims, trend alarms, or stable solvers; designs cannot be tuned or certified.

**Keep at minimum.** Distributions, confidence/credible intervals, regression, Kalman-style estimation; sparse solves, SVD/QR/LU; conditioning and preconditioning; LP/QP/NLP with constraints.

## 6.7 Control theory (classical and state-space)

**What it is.** Stability/robustness (Bode/Nyquist, margins, Lyapunov); feedback/feedforward; observers; discrete-time implementation; constraints and fault modes.

**Why indispensable.** Almost all modern systems are closed-loop. Meeting transient specs, rejecting disturbances, handling uncertainties, and ensuring safety interlocks require control design and proof of stability/robustness.

**If removed.** Overshoot, oscillations, and instability become common; safety PLCs and flight/drive controllers fail acceptance; energy systems and factories lose availability.

**Keep at minimum.** PID with anti-windup; loop shaping/margins; state-space (A,B,C,D), controllability/observability; LQR/LQG; gain scheduling; bumpless transfer; discrete-time implementation limits; fault-tolerant modes.

**Section takeaway.** These pillars carry load paths, energy/entropy accounting, EM behavior, device physics, uncertainty handling, computation, and stability. Ablating any one breaks certification, undermines KPIs, or destabilizes operations.

## 7) Case Studies by Sector

### 7.1 Civil/structural: load paths, safety factors, codes, FEA

**Artifact.** Two-span composite steel–concrete bridge;  $L/800$  deflection limit; fatigue category per code.

**Ablation under test.** Remove: RG formalism, quantum interpretations, particle-physics specifics, path-integral mechanics, gauge/differential-forms EM.

**Surrogate workflow.** Classical statics, elasticity, plastic hinge checks; code load combos; FEA with linear/nonlinear material models; weld/detail fatigue using S–N curves; EMC handled by prescriptive bonding/earthing rules.

**V&V.** Load test to  $1.0\times$  service; strain gauges vs FEA within  $\pm 3\%$ ; vibration modes within 5% of prediction; cover plates' fatigue hot spots validated via strain-life correlation.

**Result.** KPIs (deflection, stress ranges, fatigue life) unchanged within measurement noise.

**Pitfall if you drop the wrong thing.** Dropping continuum mechanics or fracture K factors breaks fatigue assessment and certification.

**Mini-contrast.** “Exotic topological phases” vs seismic detailing: no coupling. Seismic performance depends on ductility detailing and plastic mechanisms, not on high-energy physics or cosmology.

---

### 7.2 Mechanical: turbomachinery, heat exchangers, drivetrain control

**Artifact A (turbine stage).** Axial compressor stator–rotor pair; target isentropic efficiency and surge margin.

**Ablation under test.** Remove: advanced turbulence theory (keep RANS/LES practice), path integrals, RG formalism, quantum interpretations.

**Surrogate workflow.** RANS (SST), hub/tip leakage correlations, rig-calibrated loss models; map generation on test stand; surge line fit.

**V&V.** Efficiency within 0.6 points of rig; corrected speed lines aligned after bias correction; operability proven by stall margin test.

**Result.** Meets spec; no dependence on deep turbulence theory beyond validated closures.

**Artifact B (shell-and-tube exchanger).**

**Ablation under test.** Remove: non-equilibrium stat mech formalisms; keep empirical  $Nu=f(Re,Pr)$  correlations and vendor data.

**V&V.** Thermal duty within  $\pm 2\%$ ; pressure drop within  $\pm 5\%$ ; fouling allowance verified over 3,000 h run.

**Result.** Spec met with standard correlations and acceptance tests.

#### **Artifact C (EV drivetrain).**

**Ablation under test.** Remove: particle model specifics, cosmology, quantum interpretations.

**Keep.** Controls (field-oriented control), power electronics EM, thermal models, battery equivalent circuits.

**V&V.** Efficiency map, torque ripple, EMI compliance, thermal derating curves.

**Result.** No sensitivity to ablated topics; strong dependence on control theory and EM practice.

---

### **7.3 Electrical: power systems, drives, EMC, RF links**

#### **Artifact A (11 kV feeder with distributed PV).**

**Ablation under test.** Remove: gauge-theory language, RG, cosmology.

**Workflow.** Load flow, short-circuit, relay coordination, harmonic analysis using TL/circuit models; grounding per code.

**V&V.** Voltage profile within ANSI; THD < 5%; protection clears within settings margin; staged fault tests.

**Result.** Unchanged. Practical EM and control settings are the determinants.

#### **Artifact B (motor drive with EMI constraint).**

**Ablation under test.** Remove: path-integral mechanics, quantum interpretations.

**Workflow.** Switching waveform design, common-mode chokes, shields, filters; layout per EMC rules; CISPR test.

**V&V.** Conducted/radiated emissions pass with 3 dB margin; immunity verified.

**Result.** Pass without high-level formalisms.

#### **Artifact C (S-band RF link).**

**Ablation under test.** Remove: topological phases, strong-field GR.

**Keep.** Friis, link budget, noise figure, S-parameters, antenna patterns, TL reflections.

**V&V.** OTA tests match budget within 1 dB; BER at target  $E_b/N_0$ .

**Result.** No dependency on ablated topics; failure if practical EM is removed.

---

### **7.4 Chemical/process: mass–energy balances, kinetics in practice**

#### **Artifact A (amine gas sweetening unit).**

**Ablation under test.** Remove: advanced non-equilibrium stat mech; keep equilibrium/kinetics fits, mass-transfer correlations.

**Workflow.** Column design via HTU/NTU; Arrhenius kinetics; empirical mass-transfer coefficients; Aspen-like EoS.

**V&V.** Pilot column data reproduce spec within +/-5% removal efficiency; energy duty within +/-

2%.

**Result.** Meets targets; relies on balances, validated correlations, metrology.

**Artifact B (polymerization reactor).**

**Ablation under test.** Remove: RG formalism, cosmology, quantum interpretations.

**Keep.** Calibrated rate law, heat removal model, safety interlocks.

**V&V.** Batch-to-batch consistency; calorimetry confirms heat release curve; runaway margins per HAZOP/LOPA.

**Result.** Stable operation; advanced nonequilibrium theory only needed if pushing to microreactors or ultra-rapid cycles.

---

## **7.5 Aerospace (conventional): flight dynamics, GN&C, weak-field relativity only**

**Artifact A (transport aircraft wing).**

**Ablation under test.** Remove: advanced turbulence theory (retain validated closures and wind-tunnel correlation), strong-field GR, particle specifics.

**Workflow.** RANS/LES where needed; EFD correlation; loads and flutter margins via aeroelastic models.

**V&V.** Lift/drag polars within wind-tunnel uncertainty; buffet onset captured with safety margin; flutter cleared by GVT and flight test.

**Result.** Spec met; ablated theories non-participatory.

**Artifact B (GN&C for LEO satellite).**

**Ablation under test.** Remove: strong-field GR, cosmology, path-integral mechanics.

**Keep.** Newtonian gravity with J2/J4 perturbations; SR/weak-field GR for timing; state-space estimation (EKF/UKF).

**V&V.** Orbit determination residuals < target; pointing jitter within requirement; GPS time corrections applied.

**Result.** Works; dropping weak-field relativity would break timing, but strong-field topics are irrelevant.

**Artifact C (rocket engine hot-fire).**

**Ablation under test.** Remove: RG formalism, quantum interpretations.

**Keep.** Conservation, reacting-flow CFD with finite-rate chemistry, injector empirical maps, control interlocks.

**V&V.** Thrust/ISP within tolerance; stability (chug/screech) mitigated; thermal margins confirmed.

**Result.** Meets KPI; dispensability holds provided closures are validated in-regime.

---

**Section takeaway.** Across sectors, deleting high-level, non-participatory physics (HEP specifics, cosmology, interpretations, formal RG/path-integral lenses, geometric gauge language, exotic phases) leaves KPIs intact **when** balances, constitutive envelopes, practical EM, controls, numerics, and metrology remain. Where we push into edge regimes (micro/nano heat transfer, hypersonics, quantum/coherent devices), removal fails—hence the “removable with care” boundary.

## 8) Failure Modes of Wrong Removals

### 8.1 Where ablations backfire: semiconductors without band theory

**Anti-pattern.** Treating devices as pure black boxes (curve fits only) and dropping band theory entirely.

**How it fails.**

- **Temperature & bias drift.** Fits made at 25 C, Vdd=nominal, fail under cold/hot corners because carrier mobility, intrinsic carrier concentration, and junction leakage are **physics-shaped**, not arbitrary.
- **Reliability blind spots.** Electromigration (EM), bias temperature instability (BTI), hot-carrier injection (HCI), time-dependent dielectric breakdown (TDDB) all depend on field, current density, and activation energies. Without band/defect physics, lifetime derating becomes guesswork.
- **Noise & linearity surprises.**  $1/f$  and shot noise floors, intermodulation in RF chains, and laser RIN/linewidth are tied to carrier statistics and recombination channels; black-box fits miss regime changes.
- **Layout-dependent effects.** Proximity, well/substrate coupling, and body effect alter effective thresholds and capacitances; compact models encode this via band-physics-informed parameters.

**Minimal keep set (if you must simplify).**

- Diode/transistor equations with temperature scalings; mobility vs T and E-field; depletion/inversion basics; compact models (SPICE) with corner libraries; Arrhenius-style reliability models with validated activation energies.

**Audit flags.**

- PDK corners not exercised; lifetime model lacks activation energy; noise/linearity budget built only from a single sweep; laser/LED link budget ignores junction temperature.

## 8.2 Hidden dependencies through materials data and EM compatibility

**Anti-pattern.** Dropping “esoteric” physics, then importing vendor/material tables whose validity *secretly* relies on the dropped theory.

**How it fails.**

- **Properties out of envelope.** Thermal conductivity, dielectric loss tangent, permeability, or fatigue S–N data are often reported for specific frequency/strain-rate/temperature ranges; extrapolation breaks when the underlying dispersion or viscoelasticity (i.e., physics) was what made the table coherent.
- **EMC by anecdote.** Copying a filter/shield recipe from a previous program while changing cable geometry, ground scheme, or enclosure seams; near-field coupling and common-mode paths explode because Maxwell is unforgiving.
- **Process drift in composites/coatings.** Cure cycles, porosity, and anisotropy change EM and mechanical properties; ignoring process–property physics turns “same material” into a new, unvalidated one.

**Minimal keep set (if you must simplify).**

- Provenance + envelope tags on every material datum: {T, f, humidity, strain rate, cure route, RF power}.
- Transmission-line models for harnesses/PCBs (S-parameters, return paths, common-mode chokes).
- Skin depth and shielding rules-of-thumb tied to frequency and permeability; contact resistance specs for bonding.

**Audit flags.**

- Vendor datasheet used beyond stated frequency/temperature; EMC failures attributed to “mystery” when return paths are undefined; material swap approved without re-running RF/mech property checks.

---

## 8.3 When “model works” because metrology patched it—until it doesn’t

**Anti-pattern.** A simplified or wrong model appears to work because **calibration and testing** absorb its errors; later, a context shift breaks the hidden compensation.

### How it fails.

- **Calibration overfit.** Field calibration trims controllers to a narrow operating band; a new environment (altitude, humidity, supply noise) pushes the plant outside the trimmed subspace → instability or spec miss.
- **Golden-unit dependence.** Manufacturing drifts (tolerances, supplier change) move the hardware; the model's errors were canceled by one unit's quirks, not by physics; fleet performance scatters.
- **Aging and hysteresis.** Time-varying or rate-dependent behavior (creep, fouling, sensor drift) was never in the model; periodic recalibration hid it—until intervals extend or rate increases.
- **Alarm blindness.** Trend limits were set from a historically “quiet” period; when the process variable distribution shifts, control charts don't trigger because limits embed the old bias.

### Minimal keep set (if you must simplify).

- **Dual-closure discipline:** (i) physics-conservative numerics, **and** (ii) calibration plans that explicitly validate **out-of-trim** points.
- **Guardbands with provenance:** record how much of KPI margin comes from physics vs calibration.
- **Change-impact tests:** small DoE around expected shifts (T, supply, load, altitude) before release; schedule re-cals based on drift rates, not calendar only.
- **Fleet analytics:** SPC with drift detection (CUSUM/EWMA) and lot/Rev correlation to catch process-induced bias.

### Audit flags.

- Acceptance test equals calibration script (no independent check); controller retuned at every site without root cause; alarms never trip despite performance drift; DoE coverage doesn't include known field variability.

---

**Section takeaway.** Wrong removals fail in three recognizable ways: (i) **physics-limited devices** behave nonlinearly outside the lab (semiconductors/opto); (ii) **materials and EM** dependencies sneak back through data and layouts; (iii) **metrology hides bias** until context changes. The fix is not to cling to every high-level theory, but to keep the **minimal physics that anchors scalability**,

declare envelopes, and separate **what the solver enforces** from **what calibration trims**—with explicit tests for when those trims will no longer hold.

## 9) Implications

### 9.1 Curricula and licensing exams: rebalancing theory vs utility

- **Learning objectives by deliverable, not by era of physics.** Center courses on the production workflow: balances → constitutive envelopes → numerics/controls → V&V/metrology → certification. Map each lab to a code-traceable artifact (pressure vessel calc, EMC test, SIL/ASIL safety case).
- **Core that must be mastered (examined).** Newton/work-energy/momentum; Navier–Stokes + elasticity/plasticity at the level needed for FEA/CFD; 1st/2nd law and property methods; practical EM (KCL/KVL, TLs, S-parameters); semiconductor/laser basics for device selection; probability/statistics; numerical linear algebra; classical/state-space control.
- **De-emphasize (but introduce) dispensables.** RG, path-integral mechanics, quantum interpretations, cosmology beyond weak-field—teach as context modules or design-studio “lens” weeks, not gatekeeping prerequisites.
- **Assessment shift.** Replace pen-and-paper heroics with **evidence packages**: a small model, uncertainty budget, envelope declaration, and a short test plan showing how calibration closes residuals.
- **Licensing (FE/PE, EIT, DER).** Add explicit items on model-form uncertainty, applicability envelopes, EMC/EMI basics, and control robustness margins. Require candidates to identify when a surrogate is valid and when to escalate to full theory/tests.

### 9.2 Toolchains: enforce conservation, track validation envelopes

- **Conservative by construction.** Prefer finite-volume and charge-conservative solvers; require mass/energy/momentum/charge residual dashboards in every simulation report. Disallow tools without conservation audits.
- **Envelope metadata everywhere.** Attach {range: T, p, f, Re/Kn/Ma/Pe, strain-rate, humidity, cure route} to every material datum, correlation, and compact model. Tool UIs should block extrapolation without an explicit waiver.

- **Model-form uncertainty plumbing.** Support multi-model runs (e.g., RANS family switches), Bayesian calibration, and sensitivity (local + global) with automatic KPI impact summaries.
- **Calibration as first-class artifact.** Store calibration scripts, fixtures, traceability, and “out-of-trim” challenge points with the model; compute how much KPI margin comes from physics vs calibration (and flag when > X% is calibration).
- **Digital thread & regression.** CI for models: mesh/step refinement tests, solver tolerance checks, unit property consistency, and EMC return-path verifiers. Any library or PDK update triggers envelope re-validation.
- **EMC and return-path discipline.** Embed transmission-line checks, ground/bond integrity tests, and enclosure seam models as lint rules in ECAD/MCAD co-design.

### 9.3 R&D vs production: where the frontier still needs full theory

- **Keep full theory in R&D when it buys design space.**
  - **Quantum-coherent tech:** quantum information, open-system dynamics, error channels.
  - **Micro/nano transport:** non-equilibrium stat mech, rarefied/ballistic heat and mass transfer.
  - **Hypersonics/strong shocks/real-gas:** advanced turbulence, chemistry–flow coupling, radiation.
  - **Topological/strongly correlated materials:** field-theoretic/topological methods.
  - **Fusion/HEDP:** kinetic/MHD, radiation hydro, opacity models.
- **Production handoff rule.** Before migrating to production: (i) compress theory into **validated surrogates** with declared envelopes, (ii) demonstrate **transfer** across  $\geq 2$  facilities or environments, (iii) quantify **model-form uncertainty** and the calibration fraction of the KPI margin, (iv) publish a **minimum-physics set** needed to keep the product stable.
- **Two-track roadmaps.**
  - **Frontier track:** maximize insight and parameter reach; theory-heavy.
  - **Ops track:** minimize dependencies and testing burden; surrogate-heavy. Regular cross-walks decide when a result is mature enough to “descend” from frontier to ops.

- **Funding & review.** Gate R&D with “theory-to-surrogate plans” and require envelope-aware acceptance tests. Gate production with “surrogate-to-ops plans” that prove KPIs remain inside budgets without theory on the operator’s desk.

**Section takeaway.** Teach and tool for what ships: conservation-true solvers, envelope-tagged models, and calibration that’s measured—not hoped. Keep full theory alive at the frontier where it expands feasible design space; distill it ruthlessly before entering production.

## 10) Limits of This Audit

### 10.1 Edge industries (quantum tech, fusion, topological devices)

**Scope caveat.** Our “dispensability” calls do **not** generalize to sectors whose KPIs hinge on frontier physics.

- **Quantum technologies.** Coherence time, gate fidelity, quantum channel capacity, and device error models require qubit/channel formalism, open-system dynamics, and cryo/EM noise physics. Dropping them collapses performance/security claims (QRNG bias, QKD key rates, quantum sensor sensitivity).
- **Fusion & high-energy-density plasma (HEDP).** Reactor gain, stability margins, divertor heat flux, and neutron wall loading depend on kinetic/MHD, non-Maxwellian transport, radiation hydrodynamics, and opacities. “Empirical substitution” is not yet mature or portable.
- **Topological/strongly correlated materials.** Device function (quantized resistance, protected edge modes, unconventional superconductivity) is the physics. Field-theoretic/topological descriptors are not optional.
- **Semiconductor nodes at the frontier.** Below ~7 nm, variability, hot-carrier reliability, and line-edge roughness couple tightly to bandstructure and quantum transport; compact models alone are insufficient without physics-informed constraints.

**Implication.** For these domains, our Level A/B/C tiers must be **re-scored**; multiple items we labeled “safe to drop” elsewhere become **Do Not Touch** here.

---

## 10.2 Regime changes and future coupling risks

What can flip a “safe removal” into a dependency.

- **Scale transitions.** When characteristic lengths/times approach mean free paths, skin depths, coherence lengths, or relaxation times, classic closures fail (Fourier → ballistic, laminar → transitional/turbulent, lumped circuits → distributed).
- **Environment shifts.** Radiation, vacuum, cryogenic temps, high Ma/Re, strong EM fields, or corrosive media activate latent physics your surrogate never encoded.
- **Integration density.** Tighter electromechanical and thermal coupling (e.g., power-dense electronics in compact metallic enclosures) turns “ignore EM details” into EMI/thermal runaway risks.
- **Manufacturing evolution.** New materials/processes (e.g., additive manufacturing porosity/anisotropy, novel dielectrics) break inherited property tables and their hidden assumptions.
- **Regulatory drift.** Emerging standards (cyber-physical safety, EMC, functional safety) can require physics-traceable evidence you previously treated as empirical.

**Risk controls.**

- Attach **regime sentinels** to every surrogate: explicit stop-rules keyed to dimensionless groups (Re, Ma, Pe, Kn, Bi, Sr), frequency, dose, T/p.
- Maintain a **watchlist** for tech trends (node shrinks, hypersonic adoption, microreactors) that could couple dispensable physics back into mainstream products.
- Run **pre-mortems**: “If this failed, which dormant physics would be responsible?” Plan tests accordingly.

---

## 10.3 What “no effect” means in quantified tolerances

**Operational definition.** “No effect on engineering” = ablation can be absorbed while keeping **all** of the following within contract or code limits:

- **Performance drift:**  $|\Delta KPI| \leq 1\%$  (or within metrology noise if larger), against a stated measurement uncertainty and repeatability spec.
- **Safety and stability:** No reduction in factor of safety, stability margins, or certification reserves; all alarms/interlocks retain coverage.

- **Cost/schedule:**  $\leq 2\%$  lifecycle cost increase and  $\leq 5\%$  critical-path slip due only to compensating tests/guardbands.
- **Compliance:** Unchanged pass/fail against applicable standards (EMC, SIL/ASIL, pressure vessel, RF exposure, grid codes).
- **Portability:** Surrogates and calibrations **transfer across at least two** facilities/environments with the same settings and within the same tolerances.

#### Measurement discipline.

- Publish **error budgets** with allocations to model-form, parameter, numerics, and calibration; show that the ablation only shifts allocations within the existing budget (no new single-point failure).
- Report **uncertainty with provenance** (coverage factor, confidence level, traceability) and **guardband fraction**: how much of margin comes from calibration vs physics.
- Include **challenge points** (out-of-trim tests) proving robustness to expected field variability (T, humidity, supply noise, load).

#### When “no effect” is invalid.

- If tolerances shrink (e.g., higher efficiency/specs in next gen) such that the same ablation now exceeds 1% KPI or consumes critical margin.
- If the surrogate’s **applicability envelope** was never documented and later operations wander outside it.
- If **fleet variance** grows (new suppliers, process drift) and the calibration that masked model error on a golden unit no longer generalizes.

**Bottom line.** Our claims live and die by quantified tolerances. “No effect” is not a vibe; it is a repeatable statement backed by budgets, envelopes, and tests that still pass when conditions change within the declared operating domain.

## 11) Conclusion: What Carries the Load

### 11.1 The irreducible spine of engineering practice

- **Conservation at every boundary.** Discrete mass, momentum, energy, and charge balances enforced in models, code, and tests. If a solver or circuit net doesn’t conserve locally, it doesn’t ship.

- **Constitutive truth within envelopes.** Materials, flows, devices described by the simplest laws that pass data—each tagged with explicit ranges (T, p, f, Re/Kn/Ma/Pe, strain rate, humidity, cure route). Outside the envelope: escalate to richer physics or to test.
- **Numerics that respect physics.** Conservative finite volume, stable time marching, well-conditioned linear algebra, and optimization that honors constraints. Mesh/step refinement is a deliverable, not an afterthought.
- **Control as the stability contract.** Loops with quantified gain/phase margins, observers that track drift, bumpless transfer, and fault modes. Controls close the gap between model and reality—deliberately and auditable.
- **Metrology as the arbiter.** Calibrated instruments, acceptance tests with challenge points, SPC in operations, and traceable uncertainty budgets that show where margin comes from (physics vs calibration).
- **Compliance and safety cases.** Evidence packages that tie the above to codes/standards (EMC, SIL/ASIL, pressure vessels, grid codes) with residual-risk accounting.

This spine is portable across sectors and generations of technology; it is how engineered artifacts achieve performance, reliability, and certification under real constraints.

### 11.2 What can go—and why that clarity matters

- **Can go (for mainstream production):** high-energy particle specifics (CKM/PMNS, SUSY, GUTs), cosmology beyond weak-field needs, quantum *interpretations*, path-integral and RG as *formalisms*, geometric gauge/exterior-calculus packaging of classical EM/fluids, and exotic topological phases—*unless* your product *is* in those niches. Removing these does not move KPIs when the spine remains intact.
- **Removable with care:** quantum-information formalism outside coherent products; advanced non-equilibrium stat-mech outside micro/nano transport; turbulence theory beyond validated RANS/LES. These are safe only with declared envelopes, extra tests, and model-form uncertainty tracking.
- **Cannot go:** Newton/work-energy/momentum, continuum mechanics, 1st/2nd law and exergy, practical EM (circuits/waves/TLs), semiconductor/laser basics for EE, probability & statistics, numerical linear algebra & optimization, and control theory. Ablate any of these and certification, stability, or reliability fails.

#### Why this clarity matters.

- **Education & licensure:** Re-center curricula and exams on the spine; present dispensables as lenses, not gates. Graduates ship sooner and safer.

- **Tooling & process:** Invest in conservation-true solvers, envelope metadata, and calibration governance—instead of ornamental theory modules that don't affect outcomes.
- **R&D triage:** Keep full theory where it buys design space; demand plans to compress it into validated surrogates before production.
- **Risk communication:** “No effect” becomes a quantified claim with budgets, envelopes, and tests—not an opinion.

**Closing sentence.** Engineering carries load with conservation, closure, control, computation, and calibration; everything else is a lens you may choose to keep for wisdom—or set aside to ship.

## References

- [1] H. T. Oğuztöreli and A. Bejan, *Advanced Engineering Thermodynamics*, 4th ed. Hoboken, NJ: Wiley, 2016.
- [2] F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine, *Fundamentals of Heat and Mass Transfer*, 8th ed. Hoboken, NJ: Wiley, 2017.
- [3] P. K. Kundu, I. M. Cohen, and D. R. Dowling, *Fluid Mechanics*, 6th ed. San Diego, CA: Academic Press, 2015.
- [4] T. J. R. Hughes, *The Finite Element Method: Linear Static and Dynamic Finite Element Analysis*. Mineola, NY: Dover, 2000.
- [5] C. T. Kelley, *Iterative Methods for Linear and Nonlinear Equations*. Philadelphia, PA: SIAM, 1995.
- [6] G. Strang, *Linear Algebra and Learning from Data*. Wellesley, MA: Wellesley-Cambridge Press, 2019.
- [7] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.
- [8] K. J. Åström and R. M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton, NJ: Princeton Univ. Press, 2008.
- [9] K. Ogata, *Modern Control Engineering*, 5th ed. Upper Saddle River, NJ: Prentice Hall, 2010.
- [10] A. E. Bryson, *Applied Optimal Control: Optimization, Estimation, and Control*. Philadelphia, PA: Taylor & Francis, 1996.
- [11] A. H. Nayfeh and D. T. Mook, *Nonlinear Oscillations*. New York, NY: Wiley, 1979.
- [12] J. D. Anderson, *Fundamentals of Aerodynamics*, 6th ed. New York, NY: McGraw-Hill, 2017.
- [13] P. W. Atkins and J. de Paula, *Atkins' Physical Chemistry*, 10th ed. Oxford, U.K.: Oxford Univ. Press, 2014.
- [14] S. R. de Groot and P. Mazur, *Non-Equilibrium Thermodynamics*. New York, NY: Dover, 1984.
- [15] R. Kubo, M. Toda, and N. Hashitsume, *Statistical Physics II: Nonequilibrium Statistical Mechanics*, 2nd ed. Berlin, Germany: Springer, 1991.
- [16] C. Jarzynski, "Nonequilibrium equality for free energy differences," *Phys. Rev. Lett.*, vol. 78, no. 14, pp. 2690–2693, 1997.
- [17] U. Frisch, *Turbulence: The Legacy of A. N. Kolmogorov*. Cambridge, U.K.: Cambridge Univ. Press, 1995.
- [18] T. B. Gatski, J. P. Bonnet, and M. Y. Hussaini (eds.), *Quality and Reliability of Large-Eddy Simulations II*. Berlin, Germany: Springer, 2011.
- [19] D. C. Montgomery and G. C. Runger, *Applied Statistics and Probability for Engineers*, 7th ed. Hoboken, NJ: Wiley, 2018.
- [20] BIPM/IEC/IFCC/ILAC/IUPAC/IUPAP/OIML, *Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement (GUM)*, JCGM 100:2008.

- [21] CISPR 32, *Electromagnetic compatibility of multimedia equipment—Emission requirements*, IEC, 2015 (and later editions).
- [22] IEC 61000-4 series, *Electromagnetic compatibility (EMC)—Part 4: Testing and measurement techniques*, IEC, various years.
- [23] A. Bondyopadhyay, *Advanced RF and Microwave Circuit Design*. Norwood, MA: Artech House, 2015.
- [24] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ: Wiley, 2012.
- [25] S. Haykin and B. Van Veen, *Signals and Systems*, 2nd ed. Hoboken, NJ: Wiley, 2003.
- [26] J. D. Jackson, *Classical Electrodynamics*, 3rd ed. Hoboken, NJ: Wiley, 1998.
- [27] M. N. O. Sadiku, *Elements of Electromagnetics*, 7th ed. New York, NY: Oxford Univ. Press, 2018.
- [28] B. Razavi, *Design of Analog CMOS Integrated Circuits*, 2nd ed. New York, NY: McGraw-Hill, 2016.
- [29] Y. Tsididis and C. McAndrew, *Operation and Modeling of the MOS Transistor*, 3rd ed. New York, NY: Oxford Univ. Press, 2011.
- [30] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. Hoboken, NJ: Wiley, 2007.
- [31] O. Svelto, *Principles of Lasers*, 5th ed. New York, NY: Springer, 2010.
- [32] W. J. Palm, *System Dynamics*, 3rd ed. New York, NY: McGraw-Hill, 2013.
- [33] T. L. Schmitz and K. S. Smith, *Machining Dynamics: Frequency Response to Improved Productivity*. New York, NY: Springer, 2009.
- [34] A. F. Mills, *Heat and Mass Transfer*, 3rd ed. Boca Raton, FL: CRC Press, 2017.
- [35] A. B. Utgoff (ed.), *Guide for Verification and Validation in Computational Solid Mechanics*. West Conshohocken, PA: ASTM, 2012.
- [36] ASME Boiler & Pressure Vessel Code, Section VIII—*Rules for Construction of Pressure Vessels*. New York, NY: ASME, current ed.
- [37] A. A. Griffith, “The phenomena of rupture and flow in solids,” *Phil. Trans. R. Soc. A*, vol. 221, pp. 163–198, 1921.
- [38] T. L. Anderson, *Fracture Mechanics: Fundamentals and Applications*, 4th ed. Boca Raton, FL: CRC Press, 2017.
- [39] S. S. Manson and G. R. Halford, *Fatigue and Durability of Structural Materials*. Warrendale, PA: SAE, 2006.
- [40] T. J. Seebeck and G. Tsatsaronis, *Thermal Design and Optimization*. New York, NY: Wiley, 1996.
- [41] R. Smith, *Chemical Process Design and Integration*, 2nd ed. Hoboken, NJ: Wiley, 2016.
- [42] J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. New York, NY: McGraw-Hill, 2007.
- [43] N. Ashby, “Relativity in the Global Positioning System,” *Living Rev. Relativity*, vol. 6, no. 1, 2003.

- [44] R. P. Feynman and A. R. Hibbs, *Quantum Mechanics and Path Integrals*. New York, NY: McGraw-Hill, 1965.
- [45] L. E. Reichl, *A Modern Course in Statistical Physics*, 4th ed. Weinheim, Germany: Wiley-VCH, 2016.
- [46] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*. Boulder, CO: Westview Press, 1995.
- [47] J. M. Ziman, *Models of Disorder: The Theoretical Physics of Homogeneously Disordered Systems*. Cambridge, U.K.: Cambridge Univ. Press, 1979.
- [48] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information*, 10th anniversary ed. Cambridge, U.K.: Cambridge Univ. Press, 2010.
- [49] J. Zinn-Justin, *Quantum Field Theory and Critical Phenomena*, 4th ed. Oxford, U.K.: Oxford Univ. Press, 2002.
- [50] S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*. New York, NY: Wiley, 1972.

*Note:* This list blends foundational textbooks, standards, and representative research articles aligned with the paper’s themes (conservation laws, continuum mechanics, thermo, EM, controls, numerics, turbulence, non-equilibrium, quantum information, RG/path integrals, device physics, EMC, metrology, V&V).